Is Deuterium in High Redshift Lyman Limit Systems Primordial?

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ABSTRACT

Detections of deuterium in high redshift Lyman limit absorption systems along the line of sight to QSOs promise to reveal the primordial deuterium abundance. At present, the deuterium abundances (D/H) derived from the very few systems observed are significantly discordant. Assuming the validity of all the data, if this discordance does not reflect intrinsic primordial inhomogeneity, then it must arise from processes operating after the primordial nucleosynthesis epoch. We consider processes which might lead to significant deuterium production/destruction, yet allow the cloud to mimick a chemically unevolved system. These processes include, for example, anomalous/stochastic chemical evolution and D/^{4}He photo-destruction. In general, we find it unlikely that these processes could have altered significantly (D/H) in Lyman limit clouds. We argue that chemical evolution scenarios, unless very finely tuned, cannot account for significant local deuterium depletion since they tend to overproduce ^{12}C, even when allowance is made for possible outflow. Similarly, D/^{4}He photo-destruction schemes engineered to locally produce or destroy deuterium founder on the necessity of requiring an improbably large γ-ray source density. Future observations of (D/H) in Lyman limit systems may provide important insight into the initial conditions for the primordial nucleosynthesis process, early chemical evolution, and the galaxy formation process.

Subject headings: cosmology - quasars - chemical evolution - nucleosynthesis, abundances

1. Introduction

In this letter we explore issues related to the interpretation of recent putative observations of deuterium in seemingly chemically unevolved hydrogen clouds along the line of sight to QSOs. These observations presently do not provide a consistent value for the deuterium abundance, D/H, in high redshift Lyman limit sytems. Measurements in several clouds suggest a "high" value, D/H$\sim 2 \times 10^{-4}$ (Songalia *et al.* 1994; Carswell *et al.* 1994; Rugers & Hogan 1996a; Rugers & Hogan 1996b; Carswell *et al.* 1996; Wampler *et al.* 1996); while determinations in two systems yield a "low" value, D/H$\sim 2 \times 10^{-5}$ (Tytler, Fan, & Burles 1996; Burles & Tytler 1996a).

It is widely accepted that at least some of these observational inferences of D/H reflect the primordial value of this quantity at the conclusion of the big bang nucleosynthesis (hereafter; BBN) epoch. This belief is founded on the absence of viable alternative sites/mechanisms which could produce significant amounts of deuterium without overproducing other light elements such as ^{6}Li, ^{7}Li, and ^{3}He (Epstein, Lattimer, & Schramm 1976; Sigl *et al.* 1995). It is also widely noted that the low metallicities inferred for hydrogen clouds at high redshift generally imply only negligible amounts of deuterium depletion by stars.

It is important to resolve which (if any) of the various inferred D/H values represent the cosmic average primordial abundance (*cf.* Cardall & Fuller 1996; Hata *et al.* 1996). Here we use the term "average" since, in principle, there could exist intrinsic, primordial, super-horizon scale inhomogeneity at the BBN epoch (*e.g.*, isocurvature fluctuations *cf.* Jedamzik & Fuller 1995). Such intrinsic inhomogeneity could give rise to the apparent discordance in observed D/H, but only if the cosmic average of this quantity is D/H$\sim 10^{-4}$ (Jedamzik & Fuller 1995). A real discordance in D/H is, however, not well established by the data. If the apparent discordance *is* established by future observations, and it does not

arise from intrinsic inhomogeneity, then it must result from processes operating after the BBN epoch.

It may be that the apparent discordance is simply a result of some subset of the data being wrong because, for example, hydrogen "interlopers" are mistaken for isotope-shifted Lyman-α lines (Steigman 1994). An erroneous (high) D/H would result if a low column density Lyman-α forest line by chance happened to reside at the position in velocity space where the deuterium isotope-shifted Lyman-α line is expected. From the observed frequency of Lyman-α forest lines in quasar spectra (Hu *et al.* 1995), one can estimate the *a priori* probability for any one Lyman-limit system (hereafter; LLS) to have such an interloper. This probability is given by,

$$P \approx 9 \times 10^{-3} \left(\frac{(\mathrm{D/H})_p}{10^{-4}}\right)^{-0.46} \left(\frac{N_{\mathrm{HI}}}{3 \times 10^{17} \mathrm{cm}^{-2}}\right)^{-0.46} \left(\frac{1+z}{4}\right) \left(\frac{R_{\mathrm{v}}}{10 \mathrm{~km~s}^{-1}}\right) \Big(1 + \xi(\Delta v)\Big) \ , \quad (1)$$

and is seen to depend on the primordial $(\mathrm{D/H})_p$ ratio, the column density N_{HI} and redshift z of the LLS, and the observational velocity resolution R_{v}. The quantity $1+\xi(\Delta v)$ accounts for the possibility that Lyman-forest clouds may be "clustered" in velocity space around LLSs. A similar quantity, the clustering of forest clouds around each other, has been observationally estimated to be approximately $\xi(\Delta v) \sim 1$ for absorber velocity separations $\Delta \mathrm{v} \lesssim 100 \mathrm{km~s}^{-1}$ (Chernomordik 1995; Meiksin & Bouchet 1995). In practice, there is a strong observational bias to claim deuterium detections in only those clouds which show the smallest Doppler broadening of absorption lines. The expected narrow width of the deuterium line, as well as the relative widths of the deuterium and hydrogen lines, may then be used to argue against the interloper possibility on statistical grounds (Rugers & Hogan 1996a; Burles & Tytler 1996b).

Even should this issue be resolved, there are a plethora of usually hidden and implicit assumptions and decisions which must be made in any assessment of the observational data to extract a *primordial* D/H. These assumptions revolve around issues of chemical evolution

and formation histories of LLSs which show deuterium. Any such assumptions may be worrisome, given that even such basic aspects of LLSs as morphology, environment, and their masses are poorly understood. LLSs are clouds or sheets of highly ionized gas with temperatures around a few times 10^4 K and with approximate neutral column densities $N_{\rm HI} \approx 3 \times 10^{17} {\rm cm}^{-2}$. It is commonly assumed that the bulk of the gas in LLSs is ionized by the diffuse UV background at high redshift. Nevertheless, local sources for the ionizing radiation such as young blue stars (York *et al.* 1990; Gruenwald & Viegas 1993) or hot galactic halo gas (Viegas & Friaça 1995) have also been proposed. It is even difficult to eliminate entirely the possibility that a particular LLS is the result of looking through the gas of one, or a few, planetary nebulae.

It is instructive to estimate typical parameters of a LLS such as total baryon mass, spatial dimension, and total hydrogen density. Under the assumption of heating/cooling equilibrium and/or ionization equilibrium of the cloud with the background ionizing radiation, and further assuming spherical geometry for the cloud with a line-of-sight passing close to the center of the cloud, one finds: the total baryon mass,

$$M_b \approx 4 \times 10^6 M_\odot \left(\frac{U}{10^{-3}}\right)^{5.2} \left(\frac{J_0}{10^{-21}{\rm ergs\ cm^{-2} s^{-1} Hz^{-1}}}\right)^{-2} \left(\frac{N_{\rm HI}}{3 \times 10^{17} {\rm cm}^{-2}}\right)^{3} ; \tag{2}$$

the radius,

$$R \approx 2\ {\rm kpc} \left(\frac{U}{10^{-3}}\right)^{2.07} \left(\frac{J_0}{10^{-21}{\rm ergs\ cm^{-2} s^{-1} Hz^{-1}}}\right)^{-1} \left(\frac{N_{\rm HI}}{3 \times 10^{17} {\rm cm}^{-2}}\right) ; \tag{3}$$

and the total hydrogen density for the cloud,

$$n_H \approx 5 \times 10^{-3} \frac{1}{{\rm cm}^3} \left(\frac{U}{10^{-3}}\right)^{-1} \left(\frac{J_0}{10^{-21}{\rm ergs\ cm^{-2} s^{-1} Hz^{-1}}}\right) . \tag{4}$$

In these expressions U is the ionization parameter, i.e. the ratio of the density of ionizing photons (with energies $E_\gamma > 13.6$ eV) to the total hydrogen number density, and J_0 is the specific intensity of ionizing photons at $E_\gamma = 13.6$ eV. The ionization parameter is

inferred from either the relative abundances of ionization states of "metals" or the inferred temperature of the cloud (Donahue & Shull 1991). Typical uncertainties in U are about one order of magnitude implying a five order of magnitude uncertainty in the mass scale of a spherical LLS. Similarly, even under the assumption that the diffuse UV-background is the source of the ionization of the cloud, there is considerable uncertainty in J_0, translating into uncertainty in the basic cloud parameters. We conclude that not only is it difficult to determine the masses of the objects in which D/H ratios are observationally inferred, but it is also uncertain how to translate these D/H ratios into a cosmic average. In principle, it is difficult to rule out very small masses for LLSs. Such small clouds could have been subject to significant local deuterium destruction or production.

Numerical simulations (Cen *et al.* 1994; Katz *et al.* 1996) suggest that there are two broad classes of hydrogen absorption systems with hydrogen column densities sufficiently high ($\gtrsim 3 \times 10^{17}\mathrm{cm}^{-2}$) to be considered Lyman limit absorbers: (1) "field" clouds which are distinct and isolated from (proto) galactic systems; and (2) the tenuous outer regions of an otherwise massive (proto) galactic disk or halo. In the first case of isolated field clouds, the geometries are not well determined and they could be compact spherical systems or extended sheets. One may imagine that the formation and chemical evolution histories of these two classes of Lyman limit absorbers are different. The question of whether different chemical evolution histories in clouds could give rise to inhomogeneity in the observed D/H ratios requires resolution.

Chemical evolution calculations are characterized by specifications of an initial mass function (IMF) and a star formation rate. We follow the notation of Malaney & Chaboyer (1996) and take the star formation rate Ψ (in Gyr^{-1}) and the IMF $\phi(m)$ in $M_\odot^{-2}$, so that Ψ/Ω_g represents a typical inverse time scale for consumption of baryons into stars and $m\phi(m)dm$ is the fraction of mass going into stars within the stellar mass range m and

$m + dm$. Here Ω_g is the fractional contribution of cold gas in damped Lyman-α systems to the critical density and takes values of $\Omega_g \sim 0.003$ at redshift $z \approx 3 - 4$ (Lanzetta, Wolfe, & Turnshek 1995; Storrie-Lombardi *et al.* 1995). In this notation the evolution of cold gas with time can be written as,

$$\frac{d\Omega_g(t)}{dt} = -\Psi(t) + \int_{m_l(t)}^{m_{up}} (m - m_r)\Psi(t(z) - \tau(m))\phi(m)dm \ , \tag{5}$$

whereas the evolution of the deuterium mass fraction X_D with time is given by,

$$\frac{dX_D(t)}{dt} = -\frac{X_D(t)}{\Omega_g(t)} \int_{m_l(t)}^{m_{up}} (m - m_r)\Psi(t(z) - \tau(m))\phi(m)dm \ . \tag{6}$$

Here m_{up} represents the mass of the largest stars formed, m_r is the remnant mass of a star of mass m, and $m_l(t)$ is the lowest stellar mass which could have returned its gas to the interstellar medium within the age of the universe $t(z)$ (i.e. the lifetime τ of a star with mass $m_l(t)$ has to satisfy $\tau(m_l) = t(z)$).

We may approximate the evolution of the deuterium mass fraction if we assume a constant star formation rate (and IMF), neglect remnant masses, and approximate Ω_g and $m_l(t)$ as constant. This yields $X_D(t) = X_D(0)\exp(-t/\tau_D)$, with τ_D the typical time scale for deuterium destruction,

$$\frac{1}{\tau_D} = \frac{\Psi}{\Omega_g} \int_{m_l(t(z))}^{m_{up}} m\phi(m)dm \ , \tag{7}$$

such that Ψ/Ω_g is the characteristic time scale for incorporation of baryons into stars and the integral is the fraction of stellar material which has been returned to the ISM by redshift z.

It has become possible recently to derive constraints on the average star formation rate and IMF from observations of damped Lyman-α systems (Timmes, Lauroesch, & Truran 1995; Malaney & Chaboyer 1996). In order to be consistent with the observed decline in $\Omega_g(z)$ with decreasing redshift, Malaney & Chaboyer (1996) argue that typical average star formation rates are $\Psi \approx 10^{-2.5}\mathrm{Gyr}^{-1}$ for $3 \lesssim z \lesssim 4$. Star formation rates in this range would

imply a characteristic time scale for incorporation of baryons into stars of only $\sim$ 1Gyr. Discounting the possibility of outflow, and assuming IMF's close to standard (Salpeter), the predicted metal enrichment by Malaney & Chaboyer (1996) is also in rough agreement with the observed metallicities in damped systems (Lu, Sargent, & Barlow 1996). However, average deuterium destruction factors $\exp(-t/\tau_D)$ are predicted to be small ($\sim 1-5\%$) in the redshift range $3 \lesssim z \lesssim 4$, mainly because it is thought that only a small fraction of stellar material (0.1-0.2) has been returned to the ISM.

The question arises as to how one could change the IMF and/or star formation rate in evolving LLSs in order to "achieve" significant deuterium destruction. This may be done locally in stochastic chemical evolution scenarios or globally by using non-standard chemical evolution scenarios which incorporate, for example, a peaked IMF and/or mass/metal outflows. In an example taken from *galactic* chemical evolution, it has been shown recently that destruction of deuterium by a factor of 10 between epochs at high redshift and the time of solar system fromation may be possible in models which employ an early metal-rich galactic wind (Scully *et al.* 1996).

Nevertheless, stringent limits can be placed on the maximum possible deuterium destruction in individual LLSs at high redshift by stars with masses below $M \lesssim 40M_{\odot}$, provided the abundances of certain key isotopes are determined confidently. Stars have to be massive enough so that their main-sequence lifetimes are shorter than the age of the universe at redshift $z \sim 3-4$. This implies that only stars with masses $M \gtrsim 2M_{\odot}$ could have contributed to a possible deuterium depletion in the interstellar medium. Note that this lower mass cutoff is fairly insensitive to the adopted cosmology, the value of the Hubble parameter, and the precise redshift of the LLS. Stars in the mass range $2M_{\odot} \lesssim M \lesssim 4M_{\odot}2M_{\odot} \lesssim M \lesssim 4M_{\odot}$, are generally believed to be significant ^{12}C producers. The ^{12}C is transported to the surface of the star during dredge-ups, when the base of the

convective zone reaches shells which are highly carbon enriched, and subsequently returned to the ISM in planetary nebulae ejecta. The ejecta of AGB stars with $2M_\odot \lesssim M \lesssim 4M_\odot$ have typical ^{12}C/H ratios which are between 0.1 and 10 times the solar ratio, depending on stellar mass, metallicity, and the details of the dredge-up processes (Iben & Truran 1978; Renzini & Violi 1981; Forestini & Charbonnel 1996). Most models predict ^{12}C/H ratios a few times solar. More massive AGB stars, $4M_\odot \lesssim M \lesssim 8M_\odot$, may in fact be net destroyers of ^{12}C/H (cf. Forestini & Charbonnel 1996). The ejecta of massive stars $M \gtrsim 8M_\odot$, which undergo Type II supernova explosions, are generally expected to be enriched in ^{12}C, but also heavier isotopes such as ^{28}Si and ^{56}Fe with typical mass fractions of one to a few times the corresponding solar mass fraction (Woosley & Weaver 1995). Here production factors become less certain for massive stars $M \gtrsim 30 - 40M_\odot$, in particular for the heavier isotopes.

The observational determination of carbon and silicon abundances in LLSs (*e.g.*, [C/H]=-2.2 and -3.0 for the two clouds in the system at $z = 3.572$ determined by Tytler *et al.* 1996 from the observations of the carbon ionization states CII, CIII, and CIV) can be used to constrain stellar deuterium depletion. Adopting moderate carbon production of one times solar over the stellar mass range $2M_\odot \lesssim M \lesssim 4M_\odot$ and $8M_\odot \lesssim M \lesssim 40M_\odot$, and using $[C/H] = -2$ for the LLS, one can infer that not more than $\sim 1\%$ of the gas in the LLS could have been cycled through stars in the above given mass range. This implies that deuterium depletion by most stars with $M \lesssim 40M_\odot$ cannot exceed about 1%. Note that this constraint can *not* be circumvented by metal-rich winds (outflow), because the *same* stars which deplete deuterium also produce ^{12}C abundantly. Moreover, low observed ^{12}C abundances significantly reduces the possibility that a given LLS results from a line-of-sight passing through one or a few deuterium-depleted planetary nebulae.

If one imposes the constraint that significant deuterium depletion by stars must have occurred, there are only a few, seemingly highly unlikely, possibilities. Chemical evolution

could have proceeded via a sharply peaked IMF at $M \approx 6M_\odot$. Observational consequences of such a scenario may include the significant enrichment of the LLS in other isotopes, such as ^{14}N. As a second possibility, a large fraction of material may have been cycled through an early generation of supermassive stars $M \gtrsim 1000M_\odot$ which eject a substantial fraction of their initial mass in deuterium-depleted radiation-driven winds (Fuller, Woosley, & Weaver 1986) enriched only in ^{4}He. Perhaps direct inference of black hole remnants is the only way to establish the viability of such a scenario. It may be possible that the carbon abundance in a LLS is underestimated, since either the dominant carbon ionization state is CI or carbon is depleted on grains. Whereas one can place observational constraints on the CI abundance (Burles 1996), the existence of dust in LLSs is not easily observationally constrained. However, it seems unlikely that significant amounts of dust in LLSs could survive evaporation by the ambient ionizing radiation field at high redshift. Lastly, it may be that carbon production, and particularly the dredge-up processes in AGB stars, are not well understood for low-metallicity stars.

Deuterium may also be produced or destroyed by nuclear photo-disintegration in the presence of a γ-ray source: ^{4}He(γ,pn)^{2}H; ^{4}He(γ,^{2}H)^{2}H; or ^{2}H(γ,n)p. For most γ-ray sources, production of ^{2}H dominates over destruction because the number density of ^{4}He targets is much larger than that of ^{2}H targets. In fact, ^{4}He photo-disintegration has been proposed as an efficient non-BBN source for deuterium (Gnedin & Ostriker 1992), even though it has been subsequently shown that this would yield anomalously large ^{3}He/^{2}H~ 10 ratios in conflict with the presolar abundance ratio ^{3}He/^{2}H~ 1 (Sigl *et al.* 1995). In any case, in the absence of direct ^{3}He abundance determinations, one may posit that a LLS is enhanced (or depleted) in deuterium since it had once been close to a powerful γ-ray source. Assume, for example, the existence of a population of γ-ray bursters at redshift $z_b \lesssim 1000$ each of which radiates a flux with spectrum hard enough to produce γ-ray energies slightly above the ^{4}He(γ,^{2}H)^{2}H threshold, $E_{th} \approx 23\,\mathrm{MeV}$. In order for these γ-ray bursters not to overproduce

the diffuse x/γ-ray background at the present epoch, the comoving γ-ray burster density has to be smaller than,

$$N_\gamma^c \lesssim \frac{1}{(10\mathrm{Mpc})^3}\frac{1}{(1+z_b)}\left(\frac{j_\gamma(z=0, E_{th}/(1+z_b))}{10^{-5}\mathrm{MeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}}\right)\left(\frac{E}{10^{60}\mathrm{ergs}}\right)^{-1}, \tag{8}$$

where j_γ is the specific x/γ-ray intensity at the present epoch determined at the energy $E_{th}/(1+z_b)$ and $10^{-5}\mathrm{MeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ is the approximate present specific intensity at $E_\gamma \approx 20\,\mathrm{MeV}$ (Fichtel *et al.* 1977). Here E is the total energy in γ-rays above threshold in a single burst. An adopted approximate comoving distance between γ-ray bursters of $r_c \sim 10\,\mathrm{Mpc}$ should be compared to the maximum distance by which an individual LLS could have been separated from a γ-ray burst in order to still have had significant deuterium production by ^{4}He photo-disintegration. This comoving distance is,

$$r_p^c \lesssim 10^{-2}\mathrm{kpc}\ (1+z_b)\left(\frac{E}{10^{60}\mathrm{ergs}}\right)^{\frac{1}{2}}\left(\frac{(^4\mathrm{He}/^2\mathrm{H})_p}{2.8\times 10^3}\right)^{\frac{1}{2}}, \tag{9}$$

where $(^4\mathrm{He}/^2\mathrm{H})_p$ is a primordial number ratio. These distances indicate that significant deuterium production, as well as destruction, by $^4\mathrm{He}/^2\mathrm{H}$ photo-disintegration should be regarded as an improbable process.

Spatially varying (D/H) ratios at high redshift, if they exist, may have their origin in the intermediate mass scale primordial inhomogeneity of the baryon-to-photon ratio. Jedamzik & Fuller 1995 pointed out that such primordial isocurvature fluctuations may yield order unity (D/H) fluctuations on galactic mass scales ($M \simeq 10^{10} - 10^{12} M_\odot$) and fluctuations in (D/H) by a factor ~ 10 on the post-recombination Jeans mass scale ($M_J \simeq 10^5 - 10^6 M_\odot$). Nevertheless, such scenarios of BBN can only agree with observationally inferred primordial abundance constraints if a variety of criteria are met, such as the efficient collapse of high-density regions, the presence of a cutoff for isocurvature fluctuations on mass scales $M \lesssim M_J$ (cf. Jedamzik & Fuller 1995; Gnedin, Ostriker, & Rees 1995; Kurki-Suonio, Jedamzik, & Mathews 1996), and the moderate to significant ^{7}Li-depletion in low-metallicity

PopII stars. Note that contrary to recent claims (Copi, Olive, & Schramm 1996) models which predict intrinsic fluctuations in (D/H) on the LLS-scale are *not* generally ruled out by the isotropy of the CMBR. Future observations of (D/H) ratios in different LLSs may constitute the first test for the presence or absence of baryon-to-photon fluctuations on intermediate mass scales.

In conclusion, it is difficult to envision a *compelling* model for differential D/H destruction/production in LLSs that could explain the apparent observationally-inferred discordance. The logical leading candidate for such a model is anomalous/stochastic chemical evolution involving a finely tuned star formation rate or IMF. However, we have argued that most of such models may be ruled out by ^{12}C overproduction. In any case, future observations of additional LLSs showing deuterium may give insight into the resolution of this problem: either (1) mis- identification or -analysis of deuterium lines in LLSs; (2) super-horizon scale primordial inhomogeneity at the BBN epoch; or (3) very finely tuned IMF and star formation rates (*i.e.* quite different from those inferred from galactic chemical evolution considerations) in some LLSs. With the advent of the Sloan Digital Sky Survey one may expect a substantial increase in the number of known bright quasars in the near future. It has been estimated that this may yield of the order ~ 100 LLSs suitable for the determination of (D/H) ratios (Hogan 1996). With the help of this data one may gain important new insights into chemical/stellar evolution and the galaxy formation problem.

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